USINE: a new public cosmic ray propagation code

Basic phenomenology, sample results, and a bit of USINE

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Sample results obtained with the USINE code are presented. We focus on the nuclear component of cosmic-rays. We pay special attention to the determination of the secondary-to-primary ratio, the radioactive nuclei, the primary species, and finally antinuclei. We provide throughout this contribution simple toy-model descriptions of the phenomenology of these quantities. We conclude by emphasising on the structure and some features of the soon-to-be-release USINE propagation code.

Keywords: Cosmic Rays — Propagation — Code

Dead stars pervade the Galaxy and pinpoint the locations where cosmic-ray spectra built up in the past. Numerous young sources, that are still in the process of accelerating charged particles, have be recently detected with the H.E.S.S. telescope, through hadronic (pionic decay from pp collisions with the surrounding gas) and electronic (inverse Compton of the local high radiation field on high energy electrons) induced TeV energy $\gamma-$ray emissions. These charged particles then diffuse away from the sources and pervade the Galaxy, scattered off by the magnetic inhomogeneities. During this wandering, some of them escape from the Milky Way while others interact with the radiation fields and/or the interstellar gas. In the latter case, the charged particles either loose a large fraction of their energies or simply inelastically react (e.g. $pp \to \bar{p} + X$), leading to a secondary contribution to the GCR fluxes (as opposed to the primary contribution from sources). A detector seated on top of the atmosphere (TOA) will have access to the charged particles cruising around the solar neighbourhood.

The CR fluxes are largely dominated in number by protons ($\sim 90\%$), helium ($\sim 10\%$) and heavier species ($\lesssim 1\%$). The subdominant electronic component ($\sim 1\%$) plays nonetheless an important role regarding the diffuse $\gamma-$ray background. Secondary fluxes of $\bar{p}$, $\bar{d}$, positrons and γ provide the most sensitive probes for indirect detection: the annihilation of GeV to TeV mass DM particles might distort the background induced by standard secondary processes. These fluxes are calculated as a convolution of the primary p, He (and e^-) source spectra, the cross sections for the processes involved, using the gas (and the radiation field) distribution in the Galaxy and a description of the diffusion process. The charged fluxes are isotropised by the diffusion. As a consequence, i) these fluxes vary smoothly with the position in the Galaxy, ii) contrarily to γ and ν, hadronic astronomy is not possible, except at the highest energies (i.e. $\gtrsim 10^{19}$ eV). These fluxes can be directly measured at Earth, or indirectly evaluated at different locations through the so-called diffuse γ and ν emission they produce by interacting with the interstellar medium. The $\gamma-$ray emission is currently measured by the FERMI instrument, providing new insights and challenges for cosmic-ray propagation models (see Andy Strong's contribution). The ν diffuse emission is very interesting, since it has a purely hadronic origin. However, the sensitivity of existing (ANTARES, AMANDA) and future experiments (km^3, ICECUBE) might barely be sufficient to detect it. The GCR journey, from sources (with $\gamma-$ray astronomy) to their detection (fluxes of charged particles, diffuse emission...), is summarised in the schematic Fig. 1.

This contribution gives a brief overview of the results obtained with the propagation code USINE in the last few years. It focuses on the nuclear and standard component of the cosmic-ray fluxes (see Pierre Salati's contribution for the exotic component, and many other contributions for the leptons and γ-rays). We discuss i) secondary-to-primary ratios that are used to determine the value of the transport coefficients; ii) β-radioactive species that allow one to break the degeneracy between the diffusion coefficient and the halo size of the Galaxy; iii) primary species that are being measured by many recent experiments (BESS, CREAM, PAMELA, TRACER) and are deeply connected to the source spectrum; and iv) standard (and a few words on exotic) antiprotons and antideuterons. We finish with some features of the code USINE that should soon become public[a].

[a]Note that we do not have time in this contribution to talk about the many other very interesting astrophysics that can be made using all the nuclei found in the CRs (heavy nuclei, EC-decay nuclei, anomalous isotopic abundances, etc.).

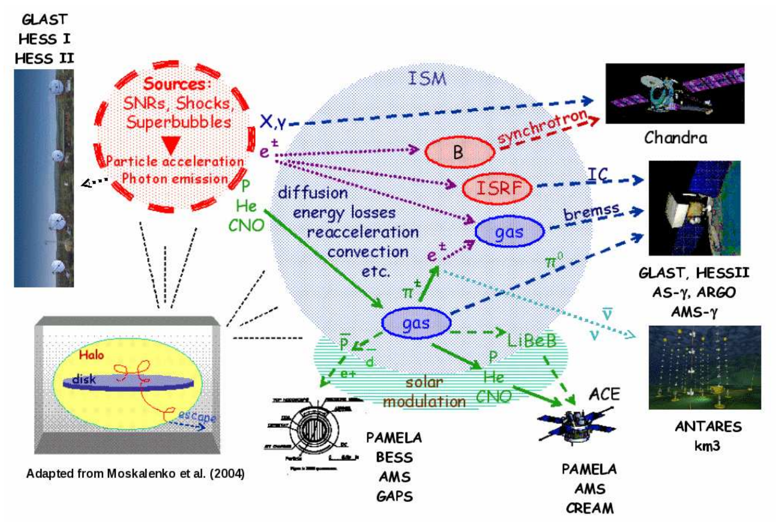

Fig. 1. Schematic view and history of GCRs: i) acceleration in sources, ii) diffusion in the Galaxy along with secondary production of antiparticles and diffuse emission, and iii) solar modulation for charged particles before detection in balloon-borne or satellite experiments. Adapted from Moskalenko et al. (2004).

1. Secondary to primary ratio

The transport equation is described in standard textbook. It generally contains a source term (standard or exotic source/production), a diffusion term, and possibly convection, energy gain and losses, and catastrophic losses (fragmentation and decay). A full numerical treatment is generally required to solve the transport equation. However, analytical (or semi-analytical) solutions may be derived assuming a simplified description of the spatial dependence of the ingredients (e.g. the gas distribution) and some transport parameters.

1.1. *Toy model*

We consider an infinite plane whose density and source distributions do not depend on r (see Fig. 2). The thin-disc approximation is used ($h \ll L$). The diffusion/convection transport equation (without energy redistributions) for a source term $q(z, E)$ reads

$$-\frac{d}{dz}\left\{K(z)\frac{dN}{dz}\right\}+\frac{d}{dz}[V_{\rm gal}(z)N]+nv\sigma 2h\delta(z)N=q(z,E). \qquad (1)$$

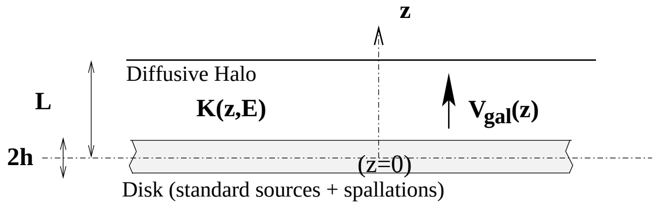

Fig. 2. Upper half-plane of the 1D infinite disc along r (half-thickness h). Cosmic rays diffuse in the disc and in the halo, with a diffusion coefficient $K(z, E)$.

The diffusion coefficient is generally assumed not to depend on the position: $K(z, E) = K(E)$. In this thin disc model, if we further drop the convective term, the transport equation reads (N is the differential number density):

$$-KN'' + nv\sigma 2h\delta(z) \times N = 2h\delta(z)Q(E).$$

For $z = 0$, the solution is

$$N(0) = \frac{2hQ(E)}{2K/L + nv\sigma} \ .$$

If we push further this simple model and neglect spallation, we have for a species present in the source term (so-called *primary* contribution) $N^p \propto Q(E)/K(E)$. For a species only produced by interaction of a primary with the interstellar medium (so-called *secondary* species), we have $N^s \propto N^s/K(E)$, such as

$$\frac{N^s}{N^p} \propto K(E).$$

The exact shape of the source term is still debated (see P. Blasi and L. Drury's contributions), but it is generally assumed to be a power-law of index ~ 2. The diffusion coefficient is generally taken to be a power-law $K(E) = \beta K_0(z)\mathcal{R}^\delta$ ($\mathcal{R}$ is the rigidity, $\beta = v/c$).

From the above equation, we note that by measuring a secondary-to-primary ratio, such as B/C, we are able in principle to determine the slope and the normalisation of the diffusion coefficient.

1.2. *Degeneracy K_0/L*

The Leaky-box equation has been used for more than forty years to successfully describe most of the nuclear components, and also the B/C ratio. The Leaky-box equation states that the CR flux is a balance between the source term and an energy-dependent probability to escape from the Galaxy. This leads to an equation, the solution of which has the same structure to that of the diffusion one above. Hence, the diffusion model parameters are related to the escape probability by

$$\tau_{\rm esc} \propto \frac{2K}{L}.$$

If a given value of the escape probability reproduces the B/C ratio, then it fixes the value of the ratio K_0/L in diffusion models. But it does not specify L or K_0 (see next section). This is the so-called degeneracy of the diffusion coefficient normalisation and the halo size of the Galaxy. This degeneracy has been known for a long time and is illustrated in Fig. 3, obtained from a study using a scan of the parameter space with the full diffusion equation.

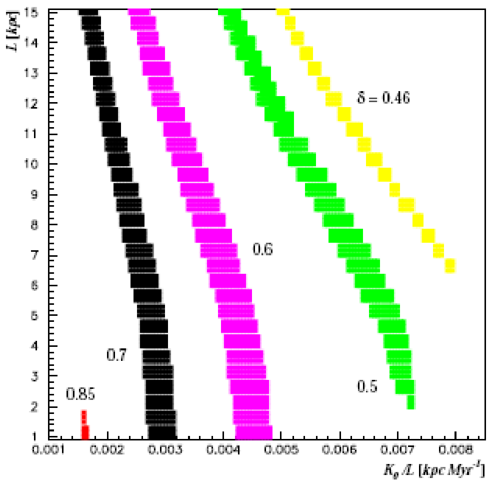

Fig. 3. For fixed values of δ, the large band show all the models consistent with B/C data. Using only stable nuclei, the degeneracy K_0/L is illustrated on this figure based on the diffusion/convection/reacceleration configuration.[1]

1.3. *Status of transport parameter determination*

Given the solution of the transport equation, it should be, in principle, simple enough to fit the B/C ratio to get a range of preferred values for the transport parameters. However, as shown in a series of studies we carried out, first based on a parameter scan analysis,[1,2] then on a more robust

Markov Chain Monte Carlo analysis,[3,4] the value of the spectral index δ of the diffusion coefficient is hardly constrained to be in the range $[0.3 - 0.8]$. Similar studies confirmed this result.[5–7] Moreover, even using radioactive species (see next section) we cannot conclude yet on the value of the halo size L.[8,9]

To understand the difficulty of pinpointing the value of δ, we remind that the most precise data fall below 100 GeV/n. In this range, the asymptotic pure diffusive regime where the toy-model equations apply is not reached: energy gains and losses as well as spallations affect this simple picture. The B/C fit is also very sensitive to the assumptions made for the input parameters (cross-sections, gas density, etc.). Indeed, the origin of the large range of values for δ can mostly be explained as follows:[9]

- if $K(E) = \beta K_0 \mathcal{R}^\delta$, models with reacceleration prefer $\delta \approx 0.3$ (as found in Ref. 10, but as soon as convection is added, $\delta \approx 0.7$;[1]
- if $K(E) = K_0 \mathcal{R}^\delta$ (leaky-box inspired), $\delta \approx 0.5$, as found in Ref. 11;
- using the parameterisation $K(E) = \beta^{\eta_T} K_0 \mathcal{R}^\delta$, negative values of η_T are possible,[12] and depending on the exact value of η_T, almost any value of δ is allowed.[9]

To summarise, extracting tight constraints on the transport parameters is already challenging using simple propagation models. It could be, as too-many-studies-to-be-quoted propose, that these simple models are far from reality: the transport coefficients may very well depend on the position, and/or diffusion is anisotropic, and/or time-dependant effects have to be taken into account, and/or secondary production during the acceleration stage is relevant at a high enough energy... Hence, despite the fact that various models in the literature can satisfactorily fit secondary-to-primary ratios such as B/C, sub-Fe/Fe, etc., we are still far from a complete and convincing picture of the details of CR propagation. Data at higher energy as well as employing other ratios (Li/C, and d/p and ^{3}He/^{4}He) may help us in this task.

2. Radioactive species

The typical distance travelled in a diffusive process in a finite time is given by $l_{rad} \sim \sqrt{Dt}$. For a β-decay unstable secondary species, it means that at low energy (plugging the typical value of the diffusion coefficient), these nuclei cannot travel farther than a few hundreds of parsecs: they do not feel the halo size L and are only sensitive to the diffusion coefficient $K(E)$. In principle, this lifts the degeneracy between K_0 and L discussed in the previous section. However, things are not as simple when we have a closer look at the hundred-of-parsec scale. It happens that there is no target to produce these species in the solar neighbourhood: we live in a local bubble.[13,14] This lack of targets affects their flux.[4,8,15]

2.1. *Toy model*

We consider a radioactive nucleus that diffuses in an unbound volume and decays with a rate $1/(\gamma\tau_0)$. In spherical coordinates, appropriate to describe this situation, the diffusion equation reads

$$-K\triangle_{\vec{r}}G + \frac{G}{\gamma\tau_0} = \delta(\vec{r}) \ . \tag{2}$$

The solution for the propagator G (the flux is measured at $\vec{r} = \vec{0}$ for simplicity) is

$$G(\vec{r'}) \propto \frac{e^{-r'/\sqrt{K\gamma\tau_0}}}{r'} \ . \tag{3}$$

Secondary radioactive species, such as ^{10}Be, originate from the spallations of the CR protons (and He) with the ISM. We model the source term to be a thin gaseous disc, except in a circular region of radius r_h at the origin. In cylindrical coordinates (see Fig. 4)

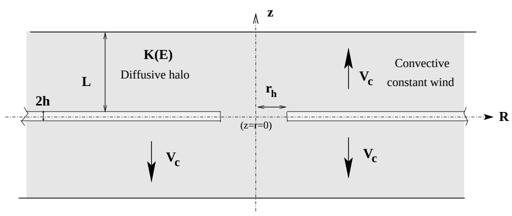

Fig. 4. Hole toy-model for the radioactive nuclei (V_c is taken to be 0 here).

$$Q(r,z) \propto \Theta(r - r_h)\delta(z) \ , \tag{4}$$

where Θ is the Heaviside function. The flux of a radioactive species is thus given by (we rewrite the propagator in cylindrical coordinates)

$$N(r\!=\!z\!=\!0) \propto \int_0^\infty \int_{-\infty}^{+\infty} G(\sqrt{r'^2 + z'^2})\, Q(r', z')\, r'dr'dz'. \tag{5}$$

2.2. *Attenuation of the flux*

The ratio of the flux calculated for a cavity/hole r_h to that of the flux without hole ($r_h = 0$) is

$$\kappa \equiv \frac{N_{r_h}}{N_{r_h=0}} = \exp\left(\frac{-r_h}{\sqrt{K\gamma\tau_0}}\right) = \exp\left(\frac{-r_h}{l_{\rm rad}}\right) . \tag{6}$$

Table 1 gathers, at a few hundreds MeV/n energy, the attenuation κ for a typical value of the diffusion coefficient (i.e. $\sim 10^{28}$ cm^2 s^{-1}) and a hole size $r_h \sim 100$ pc. This attenuation is energy dependent because it decreases

Table 1. Attenuation factor due to the local bubble for various radioactive species.

Species	τ_0 (Myr)	$l_{\rm rad}$ (pc)	κ
^{10}Be	2.17	351	0.57
^{26}Al	1.31	273	0.48
^{36}Cl	0.443	159	0.28
^{54}Mn	2.9	406	0.61

with the energy when the time-of-flight of a radioactive nucleus is boosted by both its Lorentz factor and the increase in the diffusion coefficient value. It is also species dependent because nuclei half-lives for the standard $Z < 30$ cosmic-ray clocks range from 0.307 Myr for ^{36}Cl to 1.51 Myr for ^{10}Be.

2.3. *Consequences and results*

In a grid exploration of the parameter space, we found that when included in the fit, radioactive isotopic data favour a value of $r_h \sim 80$ pc,[8] consistent with the direct measurement in the local ISM.[13] However, because of this extra parameter, the halo size L remains loosely constrained. This is discussed further in A. Putze's contribution who presents a more thorough analysis by means of an MCMC analysis.[4] Note that in Ref. 4, for the first time, the probability density function of L was given.

To summarise, the radioactive isotopic ratios are for the moment well fitted by any simple model (w/wo reacceleration, w/wo convection). However, because of the possible effect of the local underdensity, the degeneracy K_0/L is not completely lifted. Furthermore, the fit to the radioactive elemental ratios, such as Be/B is not satisfactory, regardless of the model used.[4] This is shown in Fig. 5, and the discrepancy may lie in the production cross-section of Be, or in the data, or in the propagation models themselves. The results from PAMELA should be available soon to further inspect this issue.

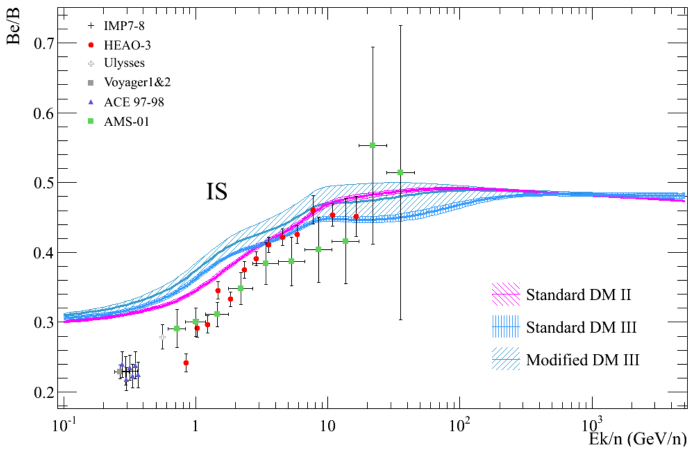

Fig. 5. Envelopes (confidence level) of Be/B for models consistent with B/C data and the radioactive isotopic ratio ^{10}Be/Be. Adapted from Ref. 4, with the recently published AMS-01 data[16] added (courtesy A. Putze).

3. Primary species

A natural question to ask is whether primary species can tell us something about the transport coefficients, or if they can only tell us something about the source parameters.

To quickly understand the phenomenology of primary species, let us start with the simplest expression for the primary flux, and then add the other ingredients:

- For diffusion only,
$$\Phi(E) \propto \frac{Q(E)}{K(E)} \propto \frac{q}{K_0} E^{-(\alpha+\delta)}.$$
There is a degeneracy in q/K_0 (q is the source term normalisation) and $\alpha + \delta$ (where α is the source spectral index): only the total spectral index is relevant in the fit, not the separate indices.
- When spallations are taken into account
$$\Phi(E) = \frac{v}{4\pi} \frac{Q(E)}{\frac{K(E)}{hL} + n\sigma v}.$$

In this Equation, $\alpha + \delta$ is now also coupled to K_0, to balance the effect of nuclear destruction at low energy: a steeper source spectrum requires more spallations to still fit the low-energy data, hence a smaller value of the diffusion coefficient.

- When energy losses and gains are considered, there is also a subtle change of the concavity and the shape of the primary spectrum, related to the strength of these effects. It can balance the need for a steeper or flatter source spectrum for instance.

From this simple analysis, we can conclude that primary species cannot alone constraint the transport parameters. A more thourough analysis shows that most of the time, it is possible to find some source parameters that allow a good match of the data, regardless of the values of the transport parameters.[17]

Figure 6 shows the typical spectrum of p and He data. At high energy ($>$ 100 GeV/n), current experiments seem to indicate a deviation from a single power-law. Waiting for more accurate data, we can still assume a

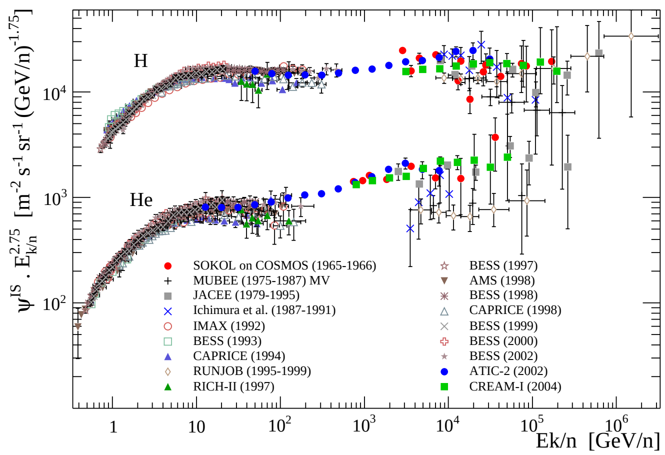

Fig. 6. Compilation of p and He demodulated data using the Force-Field (from Ref. 17).

simple power-law (no break in the slope) and, fixing the transport coefficients, try to constrain the source parameters q and α, and inspect how sensitive they are to these transport parameters. This can be achieved by means of an MCMC analysis, where the transport parameters are chosen so as to reproduce the B/C ratio. The median value and confidence levels for α for p and He are shown in Fig. 7. For a given set of data and a given configuration of the transport model (w/wo reacceleration, w/wo convection), we find that p and He have the same source spectral index within the uncertainties.[17] However, there is a large spread in the overall values. Still, whereas these different models correspond to a range of diffusion slope $\delta \approx [0.3 - 0.8]$, the source slope α only varies in the range $\sim [2.25 - 2.5]$.

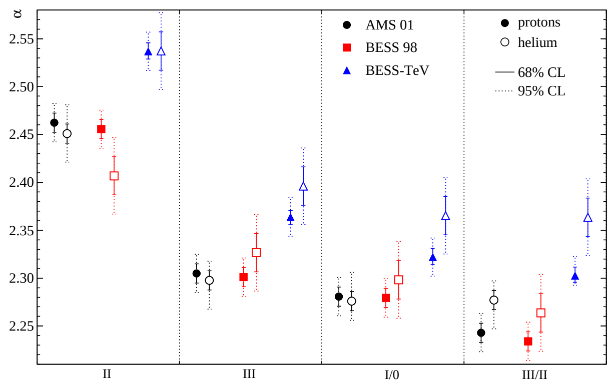

Fig. 7. Median value and confidence level on the spectral index γ fitted on p and He below-1-TeV data (from Ref. 17).

This MCMC approach is powerful and can also be applied to heavier primary species (C, O, Si, Fe...), though the uncertainties are larger than for p and He (lower statistics and larger systematics on the data). This is discussed in A. Putze's contribution. These kinds of studies have the potential to constrain the source slope and ascribe any difference in the various species, as well as inspect their source abundances. This could provide useful information for the acceleration models. Conversely, if the breaks in the data are confirmed, i.e. if source spectra are not pure power-laws, some further thinking is in order to decide how to tackle this new feature in the CR spectra (when fitting the forthcoming high-precision data).

4. Antiprotons and antideuterons

4.1. *Standard production*

Even if it happens that all the models discussed here are only *effective* models, the standard antiprotons and antideuterons fluxes can be confidently evaluated, as the propagation history of these species closely resembles that of the B production from the C primary. Indeed, p an C are both primary species located in the thin disc of the Galaxy, and they produce the secondary species by interacting in the ISM.

Such an approach was successfully followed in Ref. 18 to show that the antiprotons calculated without further fine-tuning (of the model) matched very well the data of the time. This flux was updated in Ref. 19 (but the final results is mostly unchanged) fro comparison with the recent PAMELA data, as reproduced in Fig. 8.

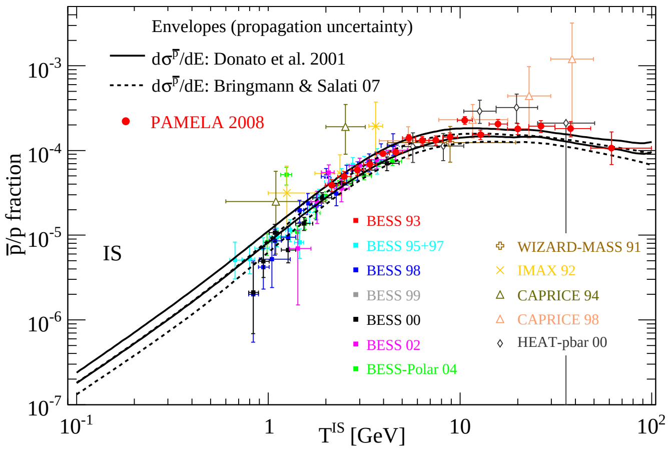

Fig. 8. Antiproton-to-proton ratio (from Ref. 19).

The same kind of calculation can be repeated for the antideuterons[20–22] for which only an upper limit exists (set by the BESS experiment). For both cases, the main source of uncertainties is from the nuclear production cross-sections ($\sim 20\%$ for antiprotons, but as large as a factor of 10 for low energy antideuterons).

4.2. *Exotic production*

In contrast, exotic sources are located in the whole diffusive halo. As a result, the propagation history is not the same as for the B/C production or for a standard primary species.

Adopting a crude model where the dark matter source term is constant in the diffusive halo of the Galaxy[23] the transport equation (no spallations) now reads

$$-KN'' = q_{\rm Dark},$$

whose solution is given by

$$N_{(\bar{p},\,\bar{d})}^{pure-DM}(z=0) = \frac{q_{Dark}L^2}{2K} = \frac{q_{Dark}\lambda_{\rm esc}L}{\mu v}\ . \tag{7}$$

For a given value of $\lambda_{\rm esc}$, i.e. a given B/C ratio, the primary flux depends linearly on L. The bigger the box containing the dark matter, the stronger the signal, which seems very reasonable. This linear dependence was observed in more realistic propagation models for decaying or annihilating dark matter.[24–27] We will not discuss this topic further and refer the reader to P. Salati's contribution for more details.

5. USINE features and public release

The package USINE deals with the propagation of Galactic Cosmic Ray nuclei (all existing nuclei) and antinuclei (antiprotons and antideuterons) in various models (LB, diffusion models...). The energy range validity (unmodulated) is between a few hundreds of MeV/nuc to PeV energies. USINE is a C++ object-oriented code that makes use of the ROOT package[b] to provide many display facilities that ease the understanding, allows quick checks, and provides graphical results (along with the data) of the propagated fluxes. The code is documented with the ROOT THtml class.

A *propagation model* is defined as i) the propagation processes themselves (diffusion, convection...); ii) the description of the medium in which CR nuclei propagate (Galaxy geometry, gas distribution in the Galaxy, spatial dependence of propagation processes); and iii) the set of equations (solutions) for the system (formed by the two previous items), which can be solved analytically or numerically. Most of the ingredients required to achieve the calculation are shared by all models.

The USINE code has been developed to calculate background and signals, for cosmic ray physics and dark matter indirect searches. However, it has also been conceived in a way to be very flexible and user-friendly for

- any experimentalist who wants to see how models can be constrained by his data;
- a nuclear physicist who wants to check how his particular set of cross sections changes the predictions of models;

[b]http://root.cern.ch/

- for a CR phenomenologist who derived a new set of equations for propagation and would like to apply it but who is usually discouraged by the huge amount of work required to compile all necessary ingredients.

The blend of semi-analytical and numerical approaches is also an advantage for validating the code.

USINE should be made public soon. Along with the code, we will also provide a database (mySQL web-interfaced database), a web-run interface, and a Graphical User Interface to ease the use of the code. We are also working on including electron, positrons and γ-rays flux for the second release.

6. Conclusion

We have presented an overview of some results obtained in the framework of diffusion/convection/reacceleration models. Such calculations were performed by means of the USINE package. A first public release of this code will appear soon.

Acknowledgments

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